3. FOREST CARBON SEQUESTRATION

This chapter presents estimates of the forest carbon sequestration that results from recycling or source reducing corrugated cardboard, magazines and third-class mail, newspaper, office paper, phonebooks, textbooks, dimensional lumber, and medium-density fiberboard.

One of the large-scale processes that influences the cycling of carbon is the uptake or release of carbon from forests. When trees are cleared for agriculture or other activities, carbon is released (generally in the form of CO_2). On the other hand, when forests are planted and allowed to continue growing, they absorb atmospheric CO_2 and store it in the form of cellulose and other materials. When the rate of uptake exceeds the rate of release, carbon is said to be *sequestered*.

In the United States, uptake by forests has exceeded release since about 1977, primarily due to forest management activities and the reforestation of previously cleared areas. This net sequestration of carbon in forests represents a large and important process. EPA estimates that the annual net CO_2 flux (i.e., the excess of uptake minus release) in U.S. forests was about 107 million metric tons of carbon equivalent (MMTCE) in 1999,[1] offsetting about 7 percent of U.S. energy-related CO_2 emissions. In addition, about 17 million metric tons of carbon was stored in wood products.

When paper and wood products are recycled or source reduced, trees that would otherwise be harvested are left standing. In the short term, this reduction in harvesting results in a larger quantity of carbon remaining sequestered, because the standing trees continue to store carbon, whereas paper and wood product manufacture and use tends to release carbon.[2] In the long term, some of the short-term benefits disappear as market forces result in less planting of new managed forests than would otherwise occur, so that there is comparatively less forest acreage in trees that are growing rapidly (and thus sequestering carbon rapidly).

Considering the effect of forest carbon sequestration on U.S. net GHG emissions, it was clear that a thorough examination was warranted for this study. The complexity and long time frame of carbon sequestration in forests, coupled with the importance of market dynamics that determine land use, dictated the use of best available models. This chapter describes our method for applying models to estimate the effect of forest carbon sequestration associated with paper and wood product recycling and source reduction.

We worked with the U.S. Department of Agriculture Forest Service (USDA-FS) to use models of the U.S. forest sector to estimate the amount of forest carbon sequestration per incremental ton of paper and wood reduced and recycled. We used the USDA-FS system of models because (1) they are the best models available in modeling the species composition, inventory, and growth of forests; and (2) these models had been used previously to analyze climate change mitigation options for the *Climate Change Action Plan*. Because the models did not enable us to estimate the forest carbon sequestration associated

[1] U.S. EPA. 2001. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*. U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC. EPA-236-R-01-001. Note that the estimate cited (110 MMTCE) includes only carbon storage in trees and understory, which is consistent with the forest components included in this report. If forest floor and soils were included as well, the total would be 171 MMTCE.

[2] The forest carbon inventory in any year equals the carbon inventory the year before, plus net growth, less harvests, less decay. Thus, when harvests are reduced, the inventory increases. However when inventories become high relative to the carrying capacity of the land, the rate of growth decreases because net growth (the rate at which growth exceeds decay) declines.

with recycling of each type of paper separately, we obtained a single estimate of the sequestration from recycling *any* type of paper.

The methodology described in this chapter finds that increased recycling of paper or wood products results in incremental forest carbon sequestration of 0.73 MTCE/ton and 0.50 MTCE/ton, respectively.[3] The USDA-FS models do not directly estimate the effect of source reduction. To derive these estimates we evaluated the mix of virgin and recycled inputs used to manufacture each material. As described later, this mix is different for each product. The resulting carbon sequestration rates range from 0.30 MTCE/ton (for corrugated cardboard) to 0.66 MTCE/ton (for phone books).

Performance of the USDA-FS Forest Models

Researchers have never formally assessed the accuracy of the USDA-FS models of the forest sector. In analyses that compare the forest impacts of a policy scenario with those of a baseline scenario (such as the analysis described in this chapter), the USDA-FS model results are probably reasonable. Much of the uncertainty in the model results is due to assumptions that apply to both the baseline and policy scenarios—assumptions about population growth, economic growth, tree growth, and land use changes. Any error in these assumptions would tend to bias the results in the baseline and policy scenarios in the same direction. Thus, when the outcomes of the baseline and policy scenarios are compared, errors in the assumptions tend to cancel each other out.

The remainder of this chapter is divided into seven parts. Section 3.1 provides an overview of the linkages between the five models used in the paper and wood analysis. Sections 3.2 through 3.5 describe the models in greater detail and briefly discuss the inputs, assumptions, and outputs for each model, focussing on the paper analysis. Section 3.6 describes the approach used to analyze wood products. Section 3.7 presents the results of the analysis, and Section 3.8 discusses the limitations of the individual models and of the analysis as a whole.

3.1 MODELING FRAMEWORK

Working with the USDA-FS, we used six models to estimate the impacts of increased recovery and source reduction of paper and wood products on forest carbon sequestration.

For paper and wood products, we used five linked models to arrive at forest carbon sequestration estimates. The first model projects the decline in U.S. pulpwood harvests when paper recovery increases. The second and third models use the outputs of the first model, together with other inputs and assumptions, to estimate the extent to which reduced pulpwood harvests due to paper recovery result in lower U.S. timber harvests and increased timber inventories.[4] The fourth and fifth models use the outputs of the second and third models, and estimate how the increased timber inventories and decreased timber harvests due to paper recovery translate into (1) increased forest carbon sequestration and (2) changes in carbon sequestration in wood-in-use carbon sinks (e.g., wood used in home construction). Exhibit 3-1 shows how the models are linked.

The paper analysis proceeded as follows:

(1) We developed two recovery scenarios − an estimated baseline paper recovery rate for the year 2000 of 50 percent and a hypothetical year 2000 paper recovery rate of 55 percent as inputs to

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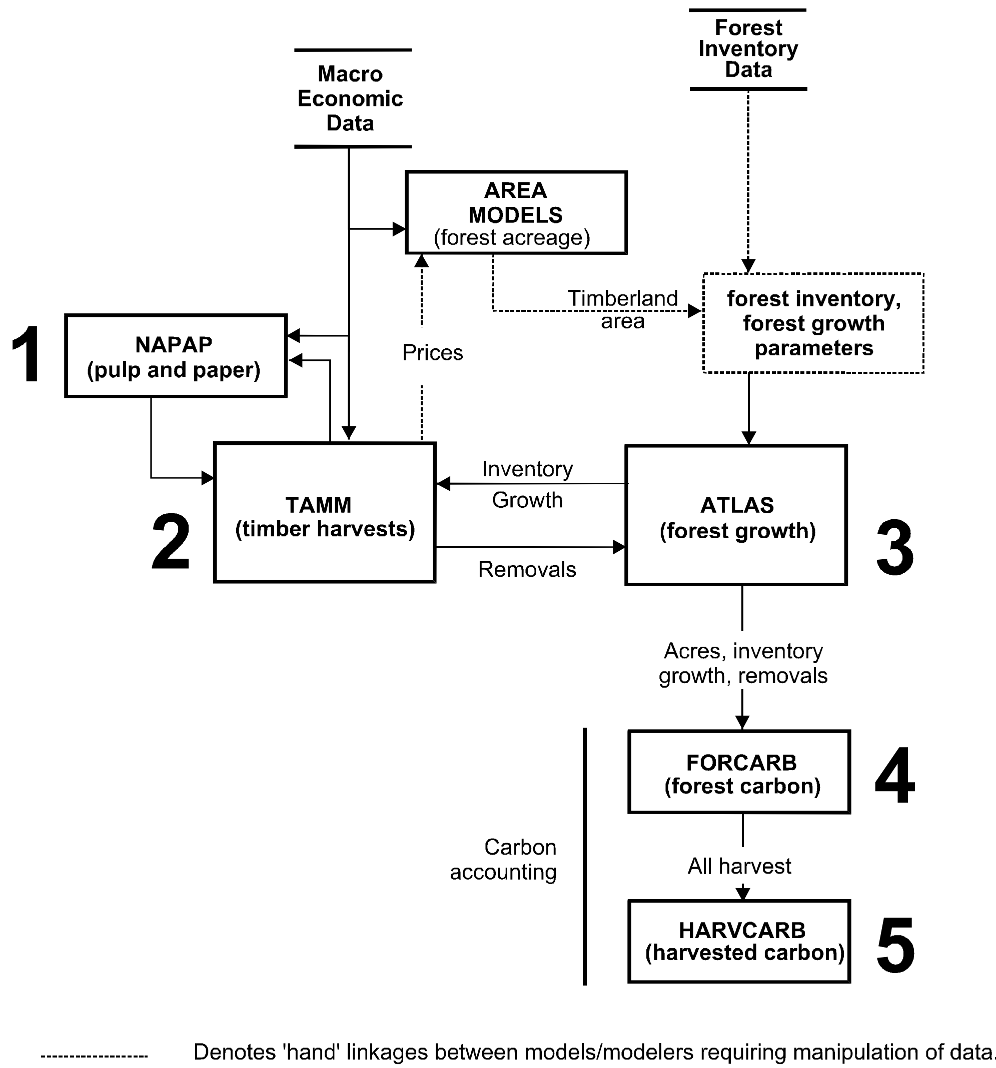
[3] Although a relationship exists, it is not directly measurable. Moreover, for the relationship to remain valid, there must be continued investment in tree planting and growth. We believe this continued investment will occur, because projections of forest product use consistently point to increases in demand.

[4] The USDA-FS projections of forest product demand account for continued high demand for all types of forest products.

Exhibit 3-1
USFS Models of the Forest Sector



the North American Pulp and Paper (NAPAP) model (the model is described in Section 3.2). The 50 percent recovery rate used for the baseline scenario was based on previous paper industry projections.[5] We used a 55 percent recovery rate for the high recovery scenario because (1) we considered this to be a plausible recovery rate with additional government programs to promote recycling, and (2) this recovery rate corresponded to EPA's goal of increasing recovery of MSW in the original (1993) Climate Change Action Plan. We then assumed that over the next 15 years, the recovery rates under both scenarios would continue to rise and would converge in the year 2016 at 57 percent. (We assumed convergence so that we

[5] Actual paper recovery in 2000 (taken from EPA's *Municipal Solid Waste in the United States: 2000 Facts and Figures*) averaged about 53%, confirming that 50 percent is a reasonable estimate for 2000.

could isolate the long-term carbon sequestration effects that might result from increasing paper recovery in the near term.) The paper recovery rates for both scenarios then were projected to rise slowly from 57 percent in 2016 to 61 percent in 2040. This adjustment to the model incorporated our assumption that the current trend of increasing paper recovery rates would continue into the future. The NAPAP model then was run to model the pulpwood harvests from 1985 to 2040 that would be associated with (1) the baseline paper recovery rate and (2) the high paper recovery rate.

(2) The outputs from NAPAP for projected pulpwood harvests in the two scenarios were used as inputs to the Timber Assessment Market Model (TAMM), which projects U.S. timber harvests, and the Aggregate Timberland Assessment System (ATLAS) model, which projects timber growth and changes in the U.S. forest inventory (where inventory is a function of both growth and harvests). The TAMM and ATLAS models are described more fully in Section 3.3. The TAMM and ATLAS models were run, using the NAPAP inputs, to generate estimates of U.S. harvest levels and forest inventories for each year through 2040, for both the baseline and high recovery scenarios.

(3) The outputs from TAMM and ATLAS for forest harvest levels and forest inventories in the two scenarios were used as inputs to the Forest Carbon (FORCARB) model, described in Section 3.4, which projects forest carbon sequestration. The FORCARB model produced, as outputs, estimates of U.S. forest carbon sequestration for each year through 2040, for both the baseline and high recovery scenarios.

(4) FORCARB outputs also were used as inputs to the WOODCARB (also known as HARVCARB, or Harvested Carbon) model, which tracks the flow of carbon in wood products (see Section 3.5).

For wood products, we used essentially the same process, but bypassed step 1 by creating a scenario involving increased recycling of wood, which causes a corresponding reduction in softwood harvest. This harvest forecast provided the basis for inputs to ATLAS, which in turn was linked to FORCARB and WOODCARB to evaluate carbon flows. As with paper, the increment in carbon storage between the base case scenario and the higher recycling scenario is calculated. This increment is divided by total tons of wood recycled to estimate a carbon storage rate (MTCE per ton of wood recycled).

3.2 THE NORTH AMERICAN PULP AND PAPER (NAPAP) MODEL

The NAPAP model is a linear optimization model[6] that uses forecasts of the U.S. economy (e.g., growth in population and the economy) to estimate the quantity of hardwood and softwood trees harvested for pulpwood in North America each year.[7] The model predicts the quantity of pulpwood harvested each year based on estimated demand and supply curves. The quantity harvested is the quantity at which these curves intersect.

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[6] A linear optimization model begins with a set of constraints (e.g., profits = revenues - costs; costs = labor costs + equipment costs + administrative costs + overhead costs) and an objective function (e.g., maximize profits). The model uses principles of matrix algebra to find the solution (e.g., the total level of output) at which the objective function is optimized (e.g., profits are maximized).

[7] A number of analyses have been conducted using results from the NAPAP models. These analyses include (1) USDA Forest Service. 1994. *RPA Assessment of the Forest and Rangeland Situation in the United States - 1993 Update*, USDA Forest Service Forest Resource Report No. 27 (Washington, DC: USDA Forest Service), 75 pp.; (2) Haynes, Richard W., Darius M. Adams, and John R. Mills. 1995. *The 1993 RPA Timber Assessment Update*, USDA Forest Service General Technical Report RM-GTR-259 (Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station), 66 pp.; (3) Ince, Peter J. 1995. *What Won't Get Harvested Where and When: The Effects of Increased Paper Recycling on Timber Harvest*, Yale School of Forestry and

3.2.1 Inputs to the NAPAP Model

The NAPAP model includes four major inputs:

- Macroeconomic forecast data (e.g., estimates of U.S. population growth and growth in per-capita gross domestic product);
- Paper manufacturing capacity as of a baseline year;[8]
- Manufacturing costs for each different paper manufacturing process; and
- Assumed levels of future harvests from public forests.

3.2.2 Equations and Assumptions Used in the NAPAP Model

The NAPAP model incorporates equations for the following functions and assumptions:

- Estimated pulpwood supply functions (reflecting an increasing supply of pulpwood at increasing market prices) for three U.S. regions (West, South, and North) and two regions in Canada;
- Estimated supply functions for four principal categories of recovered paper—newspaper, corrugated boxes, mixed papers, and the aggregate of pulp substitutes and high-grade de-inking—in each supply region (the supply functions reflect an increasing supply of recovered paper at increasing market prices);
- An unlimited supply of labor and energy at the market price in each supply region;
- A fixed-quantity supply function for residues from manufacture of solid wood products, such as lumber and plywood, mostly in the form of "pulp chips";
- Demand functions[9] for all 13 principal categories of paper and paperboard products produced in North America[10] (the demand functions reflect increasing demand due to population growth and growth in the gross domestic product, and decreasing demand due to increasing market prices);
- Functions for changes in paper manufacturing capacity (including capacity for both virgin and recycled inputs), assuming that when demand for paper increases, the investment in paper manufacturing capacity that is needed to meet demand will be made in those types of capacity where the ratio of profitability to capital cost is the highest; and

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Environmental Studies Program on Solid Waste Policy, Working Paper #3 (New Haven, CT: Yale University) 75 pp.; and (4) Environmental Defense Fund. 1995. *Paper Task Force Recommendations for Purchasing and Using Environmentally Preferable Paper: Final Report of the Paper Task Force* (New York, NY: Environmental Defense Fund), 245 pp.

[8] The baseline year for paper manufacturing capacity is 1986. The model predicts how capacity for each paper manufacturing process changes each year from 1986 onward. The model's predictions for paper manufacturing capacity in 1995, based on the 1986 baseline as updated, were within 5 percent of actual 1995 paper manufacturing capacity.

[9] Separate demand functions are incorporated for U.S. domestic demand, Canadian domestic demand, and demand from various trading regions for exported paper products from the United States and Canada.

[10] These paper grades include newspaper, coated and uncoated free sheet, coated and uncoated groundwood, linerboard, and corrugating medium.

- The ratio of the weight of paper recovered to the weight of the fiber actually used in manufacturing new paper, after accounting for discards during processing and losses during manufacturing.

The major assumptions of the NAPAP model include basic assumptions of economic analysis—i.e., that markets are perfectly competitive and that paper manufacturers seek to maximize their profits. Because owners of private forests may not always act to maximize their profits, NAPAP assumes that they will continue historical patterns of economic behavior (which USDA-FS has modeled through econometric methods). In addition, the model assumes (1) specific levels of harvests from public forests; and (2) specific future technology options.[11] Finally, the NAPAP pulpwood supply functions are the same for both the baseline and the high recycling scenario. In other words, the supply functions do not incorporate market feedbacks to account for changes in the age structure of forests or the acreage of forested land. The age structure of forests could change as increased paper recovery reduces tree harvests, so that on average trees grow longer. Forested acreage could change if higher paper recovery leads to decreased demand for pulpwood and lower pulpwood prices, leading some landowners to convert forested land to farmland or ranchland.[12]

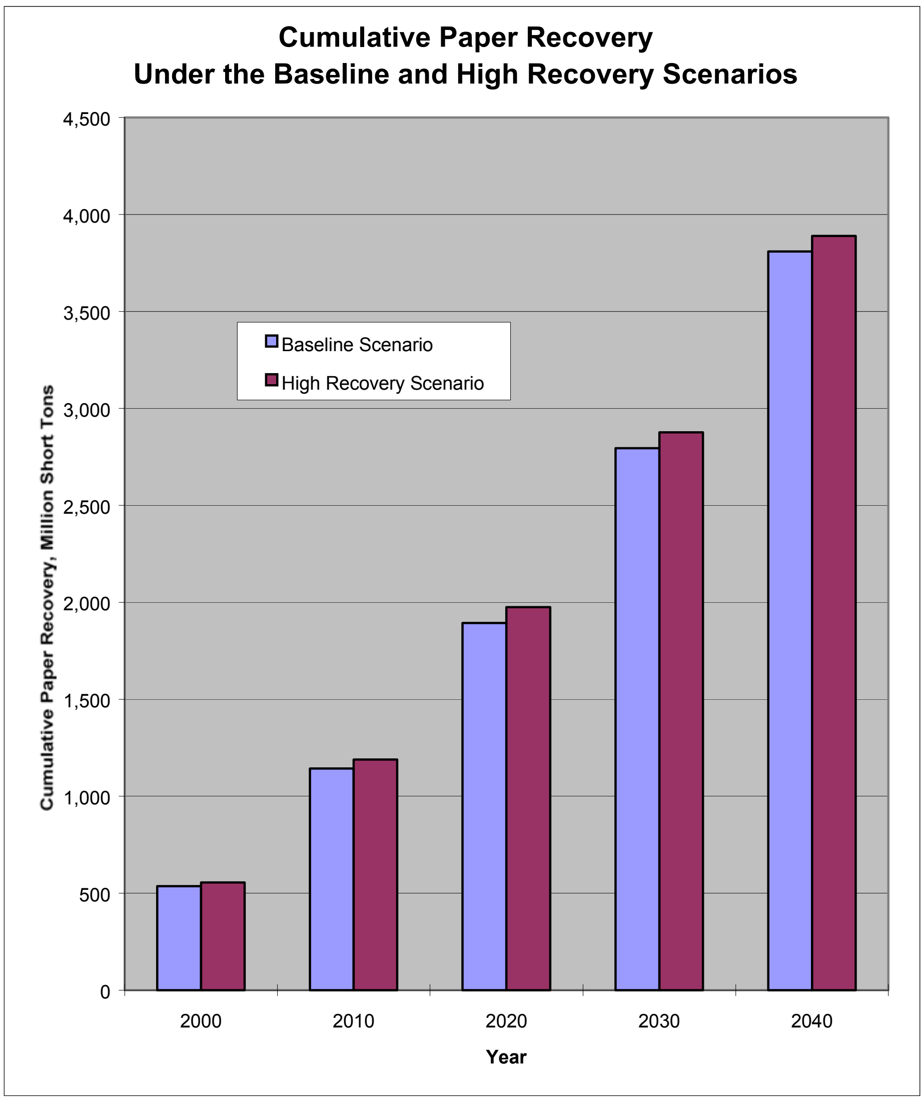
For this analysis, the USDA-FS simulated different recovery rates for the two scenarios—for the year 2000, 50 percent in the baseline scenario and 55 percent in the high recovery scenario. The cumulative amounts of paper recovered under the baseline and high recovery scenarios are shown in Exhibit 3-2.

[11] The model assumes that certain technologies that existed in 1995 but were not yet commercialized (e.g., two newspaper processes with higher yields) would enter the commercial marketplace in the period from 1995-2000.

[12] The NAPAP pulpwood supply functions incorporate projections of timber inventories over time from a prior run of the linked TAMM and ATLAS models. Ideally, the NAPAP portion of this analysis would have used two separate projections of timber inventories over time: one projection based on the baseline paper recovery scenario and another based on the high paper recovery scenario. NAPAP recently has been revised so that it may now be run iteratively with TAMM and ATLAS; however, NAPAP did not have that capability at the time this analysis was conducted.

Exhibit 3-2
Cumulative Paper Recovery
Under the Baseline and High Recovery Scenarios
(Million Short Tons)

Year	2000	2010	2020	2030	2040
A. Baseline Scenario	536	1143	1893	2795	3808
B. High Recovery Scenario	556	1189	1975	2876	3890
C. Incremental Paper Recovery Under the High Recovery Scenario (B-A)	20	46	81	81	81



NAPAP scenarios generally are specified in terms of recovered fiber utilization rates, which differ somewhat from paper recovery rates. To assure that the model inputs for fiber utilization are consistent with paper production, recovery, and consumption projections prepared by the American Forest and Paper Association (AFPA), Franklin Associates, Ltd. developed a set of conversion factors. USDA-FS used these conversion factors to adjust the demand functions for paper products. The effect was to increase the projections of paper demand and increase the estimates of the equilibrium quantity of paper produced.[13]

Trade in forest products between the United States and Canada was assumed to be fixed at levels projected in recent USDA-FS studies. As a result, any change in *North American* pulpwood harvests due to increased U.S. paper recovery would be shown in the NAPAP outputs as a change in *U.S.* pulpwood harvests. Thus, the forest carbon effects of increased paper recovery in the United States were modeled as if those effects occur entirely in the United States.

3.2.3 Outputs of the NAPAP Model

The principal outputs of the NAPAP model, for each of the two scenarios modeled, are annual U.S. pulpwood harvests from the present to the year 2040. These harvests are broken down into four categories of pulpwood: (1) softwood roundwood; (2) softwood residues; (3) hardwood roundwood; and (4) hardwood residues. The NAPAP estimates of pulpwood harvests for each scenario—for selected years from 1995 to 2040—are shown in Exhibit 3-3. As the exhibit shows, the NAPAP model projected that higher paper recovery rates until the year 2016 would result in pulpwood harvests that would be substantially below the baseline from 1995 to 2000 (because of the recovered paper substitutes for pulp that would otherwise be made from trees). From 2005 to 2010, the higher recovery scenario would result in slightly higher pulpwood harvests than under the baseline.[14] From 2020 onward, annual pulpwood harvests would be the same under the baseline and high recovery scenarios (because after 2016 the paper recovery rates would be the same in both scenarios).

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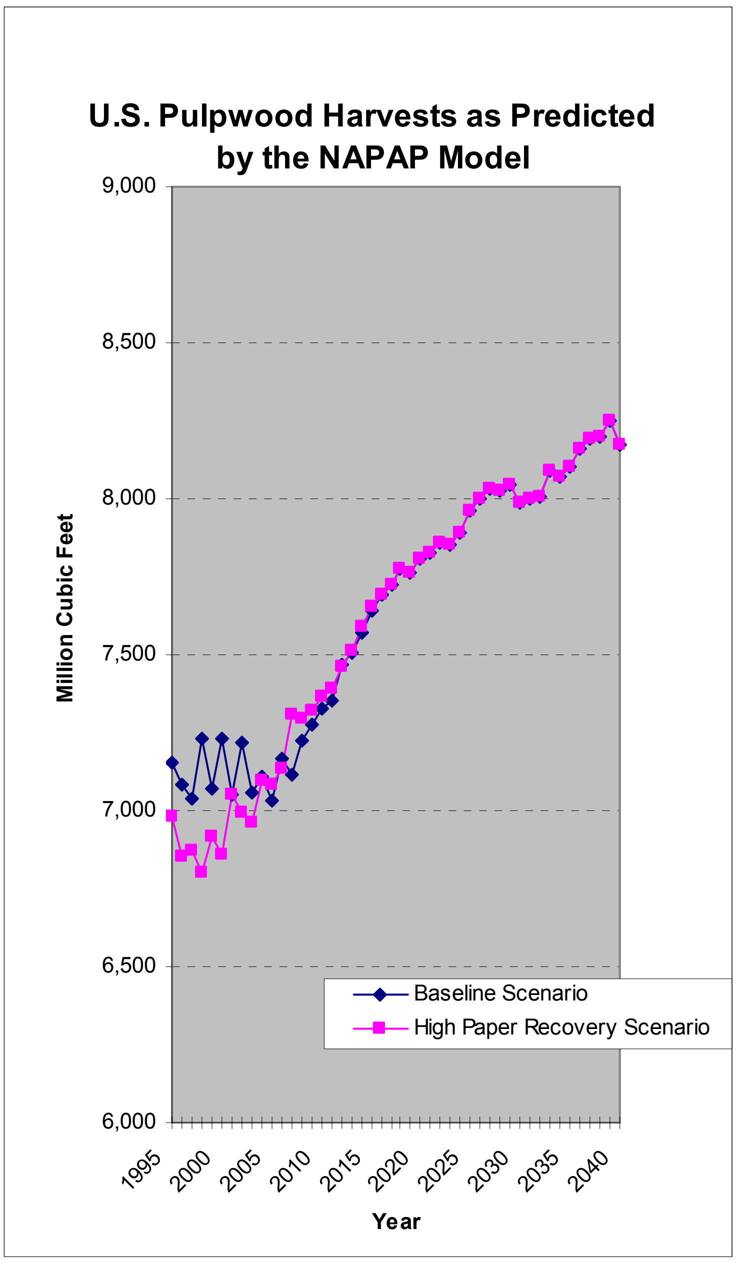
[13] Specifically, the USDA-FS adjusted the NAPAP model by increasing the elasticity of demand for paper products so that it reflected the historical relationship between (1) paper demand and (2) population and per capita gross domestic product. "Elasticity of demand" is the extent to which a change in the price of goods will affect the quantity of the goods demanded and is defined as the percentage change in quantity divided by the percentage change in price that induced the change in quantity. For example, if the quantity demanded goes down by 2 percent when the price goes up by 1 percent, the elasticity of demand is -2. Specifically, this is the "own-price elasticity" of demand because it is measured with respect to the price of the goods in question, as distinct from "cross-elasticity" of demand, which would be measured with respect to the price of different goods.

[14] Pulpwood harvests are projected to be higher between 2005 and 2010 under the high recycling scenario These harvests are expected to be higher due to the modeled consequences of reduced pulpwood harvests before 2005. Because pulpwood harvests before 2005 are projected to be lower under the high recycling scenario, more pulpwood remains to be harvested in later years. The increasing supply of pulpwood ready for harvest reduces pulpwood prices, leading to modeled increases in industry demand for non-paper uses. The increased industry demand results in slightly higher pulpwood harvests after 2005. However, it is important to note that under the baseline scenario, pulpwood harvests are projected to decline between 2000 and 2005. This decline is because the increase in paper recycling during this period is projected to be greater than the increase in paper consumption.

Exhibit 3-3
U.S. Pulpwood Harvests as Predicted by the NAPAP Model for Selected Years (Million Cubic Feet)

Year	1995	2000	2010	2020	2030	2040
Baseline Scenario	7,152	7,230	7,328	7,808	7,989	8,173
High Paper Recovery Scenario	6,982	6,858	7,362	7,808	7,989	8,173



3.3 THE TIMBER ASSESSMENT MARKET MODEL (TAMM) AND THE AGGREGATE TIMBERLAND ASSESSMENT SYSTEM (ATLAS)

TAMM and ATLAS are spatial equilibrium models.[15] TAMM models U.S. timber harvests through 2040, and ATLAS models changes in U.S. forest growth, and inventory of growing stock volume, through 2040.[16] The two models are interrelated, because timber harvests depend in part on timber inventory, and timber inventory depends in part on prior harvest levels. (This interrelationship is shown graphically in Exhibit 3-1 with arrows going in both directions between the two models.) To obtain consistency in the projections of the two models, an iterative process is used. TAMM outputs for timber removals are used as inputs to ATLAS, and the resulting ATLAS outputs for forest growth and inventory are used as inputs to TAMM. This cycle is continued until the difference in projections between one cycle and the next has been reduced to an acceptably small amount. To reduce the costs of modeling in this analysis, no hand linkages were made to transfer price estimates from TAMM back to the Area Models (see Exhibit 3-1), nor to transfer timberland area estimates from the Area Models back to ATLAS. Implicitly, the forested area was modeled as being unaffected by increased paper recovery rates.

TAMM's estimates of timber harvests are based on four factors: (1) estimated demand for solid forest products (such as softwood and hardwood lumber and panel products such as plywood) based on projected macroeconomic data (e.g., growth in population and in the economy); (2) estimates of pulpwood harvests from the NAPAP model; (3) estimates of fuelwood harvests (held constant at recent levels); and (4) estimates of annual forest growth from ATLAS.

The ATLAS estimates of forest growth and inventory are based on (1) the previous year's inventory, (2) timber harvests from TAMM, and (3) estimated forest growth parameters.

3.3.1 Inputs to the TAMM Model

The TAMM model is based on eight major inputs:[17]

- U.S. pulpwood harvests, from the NAPAP model;
- U.S. fuelwood harvests, from a fuelwood model;

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[15] A spatial equilibrium model is an optimization model (see footnote 6 in this chapter) that accounts for costs of transportation of products from producing regions to consuming regions.

[16] The descriptions of the TAMM and ATLAS models are drawn from Richard W. Haynes et al. 1993. *Alternative Simulations of Forestry Scenarios Involving Carbon Sequestration Options: Investigation of Impacts on Regional and National Timber Markets*, U.S. Department of Agriculture Forest Service, Pacific Northwest Station, August 5. Two articles which give a more detailed description of the TAMM model are (1) Adams, D.M. and R.W. Haynes. 1980. *The 1980 Softwood Timber Assessment Market Model: Structure, Projections, and Policy Simulations*, Forest Science Monograph No. 22 (Washington, DC: USDA Forest Service), 62 pp., and (2) Adams, D.M. and R.W. Haynes, *A Spatial Equilibrium Model of U.S. Forest Products Markets for Long-Range Projection and Policy Analysis*. In Andersson *et al.*, eds., "Systems Analysis in Forestry and Forest Industries," *TIMS Studies in the Management Sciences* 21(1986)73-87. Two journal articles which describe analyses based on the TAMM model are (1) Adams, D.M. and R.W. Haynes, *Softwood Timber Supply and the Future of the Southern Forest Economy*, *Southern Journal of Applied Forestry* 15(1991):31-37, and (2) Adams, D.M and R.W. Haynes. 1991. "Estimating the Economic Impacts of Preserving Old-Growth on Public Lands in the Pacific Northwest," *The Northwest Environmental Journal* 6(2):439-441.

[17] Inputs to the TAMM model are documented in: Haynes, R.W. 1990. *An Analysis of the Timber Situation in the United States: 1989-2040*, Gen. Tech. Rep. RM-199 (Ft. Collins, Colorado: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station), 286 pp.

- Assumed levels of future timber harvests from public forests, from USDA-FS harvest plans;
- U.S. net imports of forest products, from a trade model;
- Changes in U.S. forested acreage over time, from a prior run of forest Area Models;[18]
- Growth in forest inventory, from the ATLAS model;
- Macroeconomic forecast data, e.g., on U.S. housing starts, housing repairs, and remodeling; and
- Installed capacity as of 1990 for producing timber products, such as lumber or plywood, from harvested trees.

3.3.2 Equations and Assumptions Used in the TAMM Model

The TAMM model incorporates equations for the following:

- Estimated timber product supply functions (reflecting an increasing supply of timber products at increasing market prices) for eight U.S. regions; and
- Estimated demand functions for U.S. demand for all major uses of lumber and plywood (reflecting decreasing demand for such products at increasing market prices).

Also, changes in supply capacity for timber products are predicted by the model, based on anticipated changes in relative regional profitability or rate of return from capital investment.[19]

The TAMM model includes several major assumptions:[20]

- General assumptions of competitive markets, increasing demand for wood products with increasing economic activity, profit maximization by owners of lumber and plywood mills, and continued historical patterns of economic behavior by owners of forest land (these behavior patterns may not be strictly profit maximizing); and
- Specific assumptions regarding particular levels of public harvests and projected changes in technology.

In addition, TAMM and ATLAS assume (1) specified levels for net imports of softwood products, and (2) no net imports of hardwood lumber.

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[18] In the NAPAP portion of this analysis, timber inventories over time were not affected by the different paper recovery rates in the two different scenarios analyzed, but in the TAMM and ATLAS models, timber inventories were estimated independently for the two different scenarios.

[19] Specifically, TAMM uses an assumption that changes in capital investment are a function of past changes in output (i.e., that manufacturers' expectations about the profitability of capital investment are based on past changes in output).

[20] Assumptions of the TAMM model are documented in the following two reports: (1) Haynes, R.W. 1990. *An Analysis of the Timber Situation in the United States: 1989-2040*, Gen. Tech. Rep. RM-199. (Fort Collins, Colorado: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station), 286 pp.; and (2) Haynes, R.W., D.M. Adams, and J.R. Mills. 1995. *The 1993 RPA Timber Assessment Update*, Gen. Tech. Rep. RM-GTR-259 (Fort Collins, Colorado: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station), 66 pp.

3.3.3 Inputs to the ATLAS Model

The ATLAS model, for each simulation year, relies on four major inputs:

- Forest inventory at the beginning of the previous period, from a prior ATLAS model run;
- Forest removals during the previous period, from the TAMM model;
- Changes in forest acreage, from a prior run of a modified version of the Southern Area Model; and
- State-by-state data on the number of forested acres and the volume of timber per forested acre (shown as "Forest Inventory Data" in Exhibit 3-1).

3.3.4 Equations and Assumptions of the ATLAS Model

The ATLAS model incorporates equations that allow the model to simulate shifts in forest management intensities and consequent changes in yields. Projected shifts in forest management intensities are based on (1) the modeled prices of forest products, (2) the costs of various management practices, and (3) the timber yields associated with each management practice.

The only major assumption in the ATLAS model is that owners of private forests manage their forests at the level of intensity indicated by recent average forest planting rates. Otherwise, the model is very simple, relying on a basic mathematical proposition that forest inventory in any period equals forest inventory in the previous period, plus net growth, minus harvests. Net growth is gross growth less mortality from fire, storm, insects, and disease.

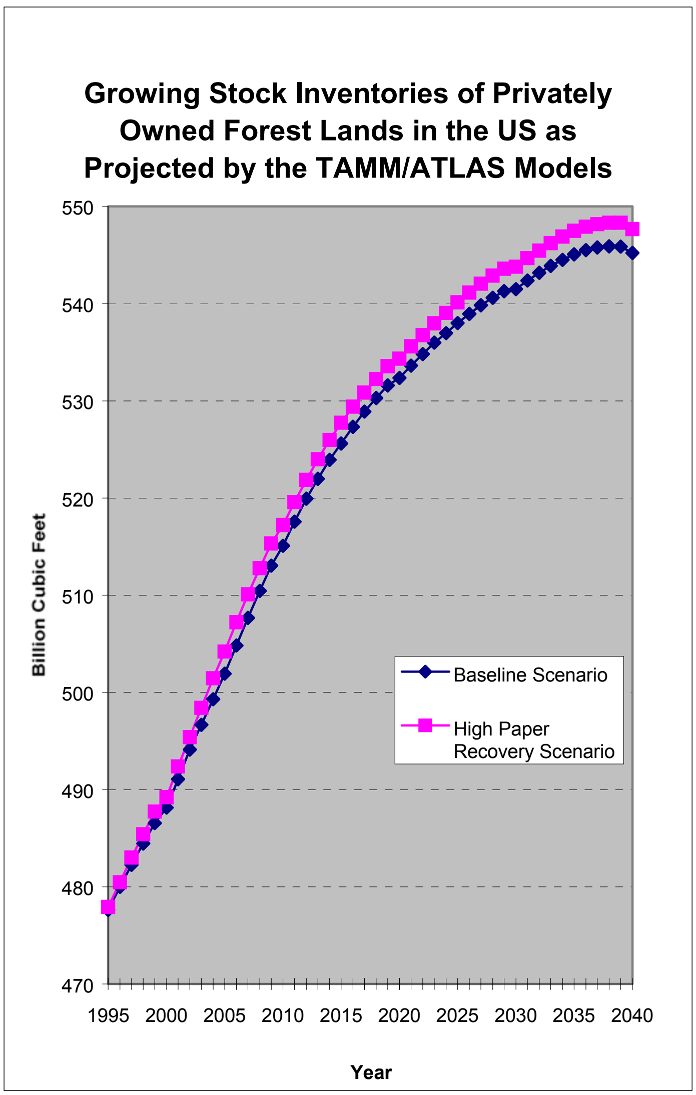
3.3.5 Outputs of the TAMM/ATLAS Models

The outputs of the linked TAMM and ATLAS models are projections, through 2040, of U.S. inventories of forest growing stock volumes (i.e., the volume of trees growing in forests), annual U.S. sawtimber harvests, and forest growth.

We used the TAMM/ATLAS data on forest growing stock inventories as inputs to FORCARB. Exhibit 3-4 shows the growing stock inventories of privately owned forest lands in the United States as projected by the TAMM/ATLAS models. As the exhibit shows, forest growing stock inventories range from 1 to 2 billion cubic feet higher under the high recovery scenario than under the baseline scenario for the entire simulation period.

Exhibit 3-4
Growing Stock Inventories of
Privately Owned Forest Lands in the US
As Projected by the TAMM/ATLAS Models
(Billion Cubic Feet)

Year	1995	2000	2010	2020	2030	2040
Baseline Scenario	478	488	515	532	541	545
High Paper Recovery Scenario	478	489	517	534	544	548



3.4 THE FOREST CARBON MODEL (FORCARB)

The Forest Carbon Model (FORCARB) projects U.S. forest carbon sequestration (including soil, forest floor, and understory carbon) each year through 2040, based on outputs from the TAMM/ATLAS linked models.[21]

3.4.1 Inputs to the FORCARB Model

The major inputs to the FORCARB model are the following:

- Forest growing stock inventories—by tree species, age, and region—from the linked TAMM/ATLAS models; and
- The percentage carbon composition for different species of trees, as grown in different forest regions.

3.4.2 Assumptions of the FORCARB Model

The USDA-FS tracks information in TAMM/ATLAS in terms of growing stock volume, i.e., the merchantable portion of trees. Tree volume is larger than growing stock volume, due to additional volume in non-merchantable portions of the tree such as roots and branches. The FORCARB model uses the simplifying assumption that tree volume is a constant multiple of growing stock volume. Carbon in the tree volume in the U.S. forest industry then is estimated based on the percentage carbon content of different species of trees.

When a tree is harvested, FORCARB no longer counts the carbon remaining in the non-merchantable portion of the tree (e.g., tree roots) following harvest. In other words, FORCARB uses the simplifying modeling assumption that the carbon in the non-merchantable portion of the tree is no longer sequestered and is converted to CO_2 emissions.

3.4.3 Outputs of the FORCARB Model

As outputs, the FORCARB model produces estimates of total U.S. forest carbon inventories and estimates of sawtimber and pulpwood harvests for each year through 2040. The amount of forest carbon sequestration in a given year equals the increase in forest carbon inventories during that year. If forest carbon inventories decrease, net emissions, i.e., negative forest carbon sequestration, would occur.

Exhibit 3-5 shows the projected carbon inventories of U.S. forests, as projected by the FORCARB model, for the baseline and high paper recovery scenarios. The forest carbon inventories that served as the basis for these annual changes counted carbon in trees and understory (e.g., small trees), but not carbon in the soil and forest floor. These carbon stocks were not included because of the high level of uncertainty in estimating and modeling their carbon content.

[21] The description of the FORCARB model here is drawn from Birdsey, Richard A., and Linda S. Heath. 1993. *Carbon Sequestration Impacts of Alternative Forestry Scenarios - Draft* (Radnor, PA: U.S. Department of Agriculture Forest Service, Global Change Research Program), pp. 47-51. A number of studies analyzing forest issues using the FORCARB and HARVCARB models have been published in journal articles. Among these are three that also explain the FORCARB and HARVCARB models. These three articles are (1) Plantinga, A.J. and R.A. Birdsey. 1993. "Carbon Fluxes Resulting from U.S. Private Timberland Management," *Climatic Change* 23:37-53; (2) Heath, L.S. and R.A. Birdsey. 1993. "Carbon Trends of Productive Temperate Forests of the Coterminous United States," *Water, Air, and Soil Pollution* 70:279-293; and (3) Heath, L.S. and R.A. Birdsey. 1993. "Impacts of Alternative Forest Management Policies on Carbon Sequestration on U.S. Timberlands," *World Resource Review* 5:171-179.

Exhibit 3-5
U.S. Forest Carbon Inventory, Trees, Understory, Soil, and Forest Floor
As Predicted by the FORCARB Model
(Million Metric Tons of Carbon)

Year	2000	2010	2020	2030	2040
A. Baseline Scenario	8,641	9,076	9,322	9,442	9,497
B. High Paper Recovery Scenario	8,665	9,118	9,364	9,480	9,537
C. Incremental Carbon Stored Under the High Paper Recovery Scenario (B-A)	24	42	42	38	40

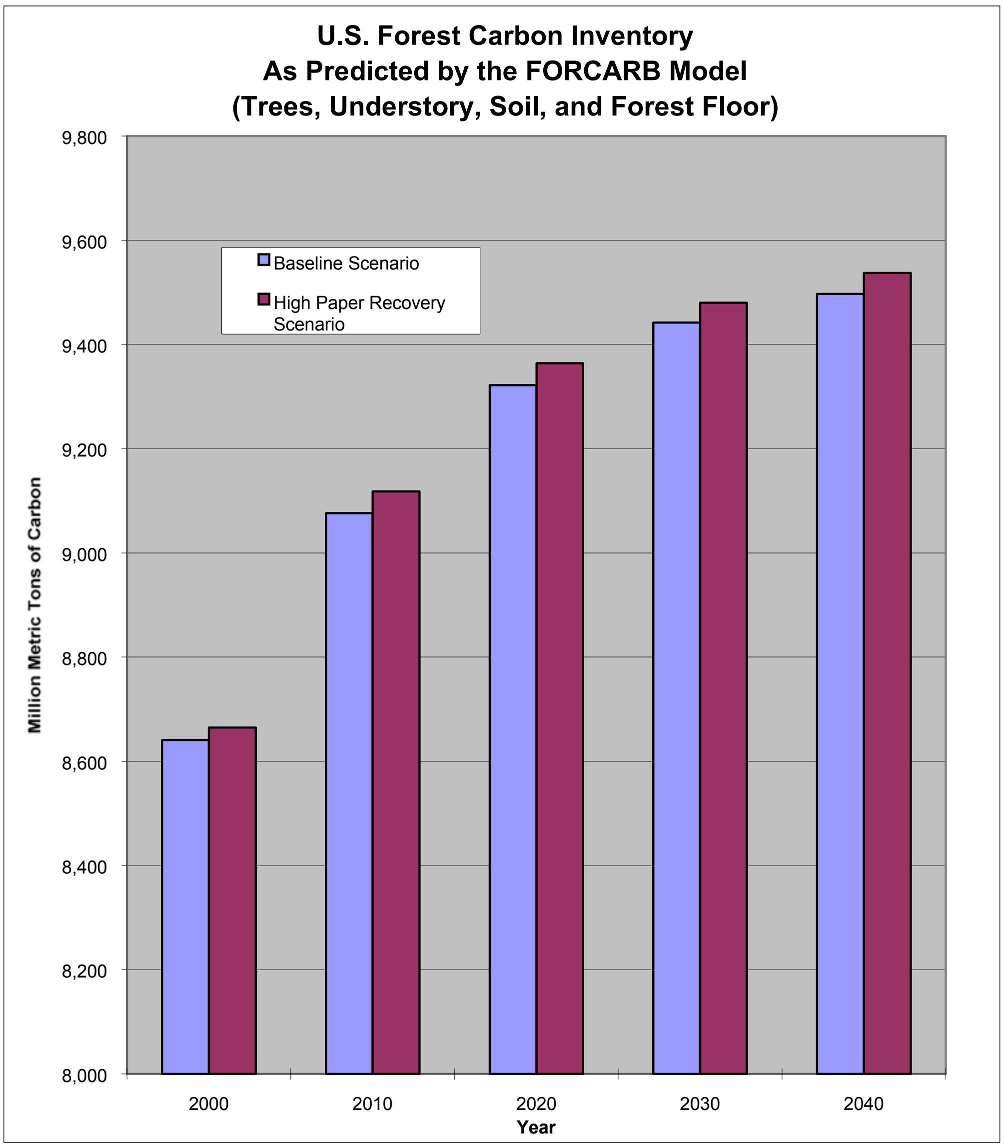


Exhibit 3-6 shows the *change* in U.S. forest carbon inventories, expressed as an annual average for decades from 2000 to 2040. Inventories increase more quickly under the high recycling scenario than under the baseline recycling scenario, through the decade ending 2010. After 2010, the rate of increase in forest carbon inventories is essentially the same for both scenarios. This consistency is because the paper recovery rate is modeled as converging in 2016 to the same rate in both scenarios.

3.5 THE HARVESTED CARBON MODEL (WOODCARB)

WOODCARB (also known as the Harvested Carbon Model, or HARVCARB) can be thought of as a spreadsheet model that projects the disposition of harvested wood across four different potential scenarios, for 50 years into the future.[22] The spreadsheet would include estimates of the percentage of four categories of wood that will be found in four potential fates at 10-year intervals: (1) products (a "wood-in-use" sink); (2) landfills; (3) combustion for energy; and (4) aerobic decomposition. Some change in the fate of a wood product occurs over time: wood products that are in use in the early years are likely to be landfilled or combusted in later years. The four different categories of wood considered in the model are softwood and hardwood pulpwood, and softwood and hardwood sawtimber. The model has separate fate estimates for three regions of the United States: west, south, and north.

We combined the average annual sawtimber and pulpwood harvest estimates from FORCARB with the fate estimates in the WOODCARB spreadsheet, to obtain estimates of the amount of carbon from harvested wood that would be found in each of the four potential fates for 50 years into the future.

3.5.1 Inputs to the WOODCARB Model

As the only input to the WOODCARB model, the USDA-FS used the annual sawtimber and pulpwood harvests from the FORCARB model.

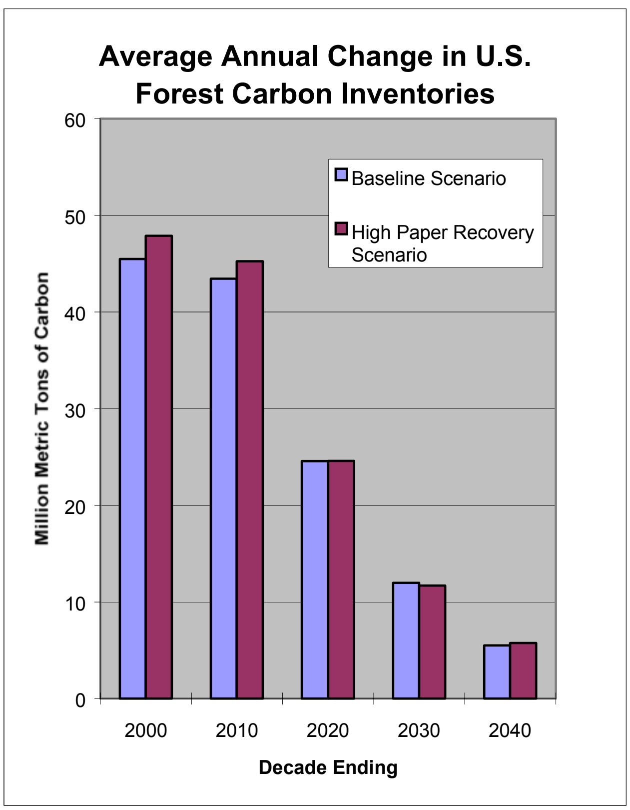
3.5.2 Assumptions of the WOODCARB Model

The WOODCARB model assumes that the material management patterns for the four categories of wood over a 50-year period do not change (e.g., the model does not assume any change in the proportion of waste or disposed wood burned for energy).

[22] This USDA-FS model is an adaptation of the HARVCARB model developed earlier (C. Row, and R.B. Phelps, 1990, "Tracing the flow of carbon through the U.S. forest products sector," Presentation at the 19th World Congress, International Union of Forestry Organizations, 5-11 August 1190, Montreal, Quebec), and described more fully in Row and Phelps, 1996, "Wood Carbon Flows and Storage after Timber Harvest," in Forests and Global Change. Vol 2, R. Neil Sampson and Dwight Hair, eds. American Forests, Washington, DC, p 27-58. This description of the USDA-FS implementation of the model is based on R.A. Birdsey and L.S. Heath, *op cit*, pp. 50-51.

Exhibit 3-6
Average Annual Change In U.S. Forest Carbon Inventories As Predicted by the FORCARB Model (Million Metric Tons of Carbon)

Time Period	Decade Ending 2000	Decade Ending 2010	Decade Ending 2020	Decade Ending 2030	Decade Ending 2040
A. Baseline Scenario	45.48	43.47	24.56	11.96	5.52
B. High Paper Recovery Scenario	47.89	45.25	24.59	11.70	5.74
C. Incremental Annual Forest Carbon Sequestration in the High Paper Recovery Scenario [B-A]	2.40	1.79	0.03	-0.26	0.22



3.5.3 Outputs of the WOODCARB Model

In this analysis, WOODCARB provided outputs for the amount of carbon (1) retained in wood-in-use sinks; (2) landfilled; (3) combusted for energy; and (4) aerobically decomposed, for each year from 1995 to 2040. Because other parts of our analysis address landfills and combustion, and aerobic decomposition has no GHG effects, we used only the estimates of the amount of carbon retained in wood-in-use sinks (a form of carbon sequestration). We included this amount in our estimate of total "forest carbon," even though this carbon is stored in locations outside of forests.

Exhibit 3-7 shows the wood-in-use sinks for the baseline and high recovery scenarios from 1990 to 2040, as predicted by the WOODCARB model. As shown in the exhibit, the wood-in-use sinks are slightly less under the high recovery scenario than under the baseline scenario. The WOODCARB model predicts this result because under the high recovery scenario, tree harvests are reduced. Under the fixed proportions of the fates of wood assumed in WOODCARB, less wood is available for each of the fates for wood products, including wood-in-use sinks. As noted above, WOODCARB uses fixed proportions for the disposition of harvested wood (e.g., paper, housing, and furniture). With increased paper recovery, wood prices would be expected to decline (due to reduced demand), and more wood probably would be used for housing and furniture. Because WOODCARB does not account for any change in the price of wood and its impacts on wood-in-use sinks, the values in Exhibit 3-7 are probably a slight underestimate of the amount of carbon in wood-in-use sinks under the high recovery scenario.

3.6 APPLYING THE MODELS FOR WOOD PRODUCTS

As the preceding discussion indicates, the USDA-FS modeling system is quite complex and requires extensive coordination between model components. The modeling of the effects of paper recycling and source reduction was conducted over a 2-year period and involved efforts of several experts. After publication of the first edition of this report, EPA received several requests to evaluate the effect of recycling and source reduction of solid wood products, especially dimensional lumber and medium-density fiberboard. For these products, the USDA-FS, EPA, and ICF Consulting conducted a more streamlined analysis to characterize forest carbon flows.

The streamlined analysis bypassed the use of NAPAP and TAMM. Rather than creating a market-based harvest scenario by using these models, a harvest scenario was developed based on the expert judgment of two USDA-FS experts in forest products and carbon flows: Dr. Ken Skog of the Forest Products Laboratory and Dr. Linda Heath of the Northeast Research Station. Dr. Skog indicated that the majority of solid wood products are derived from softwood, and a large-scale wood recycling program might result in a corresponding reduction in softwood harvest of about 1.7 percent. This harvest forecast provided the basis for inputs to ATLAS, which in turn was linked to FORCARB and WOODCARB to evaluate carbon flows.

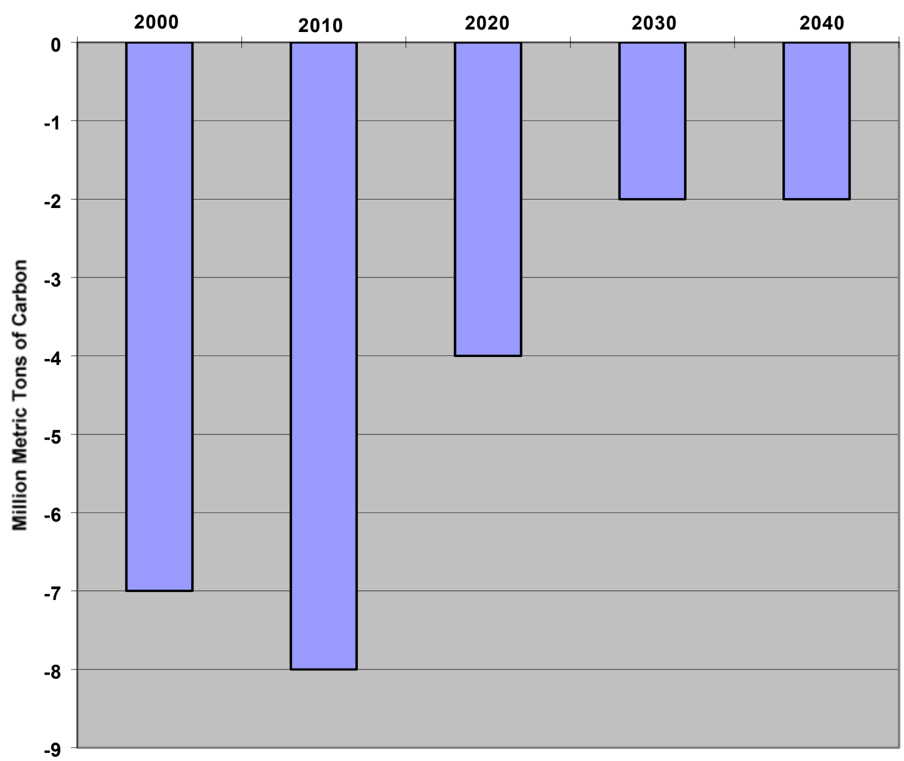
The reductions were distributed throughout the USDA-FS regions in proportion to baseline harvest for the period 1998-2007. The cumulative reduction in softwood harvest was 26.4 million short tons.

The effect of this reduction in harvest is to increase carbon sequestration in forests. To be consistent with the approach for paper recycling, effects were analyzed only for the tree and understory components (and excluded forest floor and soils). The total carbon sequestration was converted to a rate per increment of (a) recycling or (b) source reduction. Dr. Skog provided the following rough estimates of the system efficiencies, on a mass basis, for producing wood products from virgin inputs or recycled inputs:

Exhibit 3-7
U.S. Cumulative (Since 1990) Wood-in-Use Sinks as Predicted by the HARVCARB Model (Million Metric Tons of Carbon)

Year	2000	2010	2020	2030	2040
A. Baseline Scenario	733	1,216	1,634	2,028	2,381
B. High Paper Recovery Scenario	726	1,208	1,630	2,026	2,379
C. Change in Carbon Storage in Wood-in-Use Sinks [B-A]	-7	-8	-4	-2	-2

Change in Carbon Storage in Wood-in-Use Sinks Between the Baseline and High Paper Recovery Scenarios, as Predicted by the HARVCARB Model (Million Metric Tons of Carbon)



- 1.1 tons roundwood input per ton finished product; and
- 1.25 tons recycled wood input per ton of finished product.

Based on these factors:

- For every ton of solid wood product that is source reduced, the reduction in timber harvest is 1.1 tons; and
- Assuming that overall demand for wood products is constant, increases in recycling reduce timber harvest so that for every ton of solid wood product recycled, the reduction in timber harvest is 0.88 tons (=1.1/1.25).

To develop estimates of the incremental forest carbon sequestration rates, we divided the change in forest carbon sequestration by the rates of recycling or source reduction that correspond to the reduced tonnages of softwood harvest.

The final step was to estimate effects on the product pool. For wood products, we assumed a carbon density of 0.531 tons C/ton wood (or 0.48 MTCE per short ton wood), corresponding to softwoods in a Southeast and South Central pine forest (one of the principal sources of softwood harvests), based on Birdsey 1992.[23] Other key assumptions were the following:

- For source reduction, every ton of wood product removed from the product pool results in a corresponding decline in carbon mass in that pool; and
- For increased recycling (i.e., at levels above the current rate), every 1 ton of wood recycled yields 0.8 ton of product (=1/1.25). According to Dr. Skog, it is reasonable to assume that the mass lost in the recycling process is burned. Thus the carbon loss from the product pool is (1 ton wood recycled - 0.8 ton wood retained) * 0.48 MTCE/ton wood = 0.10 MTCE/ton.

Note that the effect on the product pool from both source reduction and recycling is to decrease carbon sequestration. This decrease offsets some of the benefit of increasing sequestration in the forest pool.

3.7 RESULTS

As noted at the beginning of this chapter, we first obtained estimates of the forest carbon sequestration[24] from paper recycling, and then used those estimates to develop estimates of the forest carbon sequestration from source reduction of paper.

We estimated the forest carbon sequestration per ton of paper recycled at various points in the future by dividing the *cumulative difference* in forest carbon between the high recovery and baseline scenarios by the *cumulative difference* in the amount of paper recovered between the two scenarios. To estimate the forest carbon sequestration in each scenario, we summed the forest carbon sequestration estimates generated by the FORCARB model and the wood-in-use sink estimates generated by the WOODCARB model.

The USDA-FS projected forest carbon inventories under the baseline and high recovery scenarios at several points in time (i.e., 2000, 2010, 2020, 2030, and 2040). The estimates of incremental forest carbon sequestration per ton of paper recovered vary across time, as shown in Exhibit 3-8. Note that the estimates of incremental forest carbon sequestration decline from 2000 to 2020, and then stabilize.

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[23] Birdsey, Richard A. 1992. *Carbon Storage and Accumulation in the United States Forest Ecosystems*. USDA Forest Service. General Technical Report WO-59. Table 1.2

[24] As noted earlier, the term *forest carbon sequestration* is intended to include both the carbon stored in forests and the carbon stored in wood-in-use sinks.

We chose the forest carbon sequestration factor for the period ending in 2010 as the best approximation of the forest carbon benefits from increasing source reduction and recycling over the near term. This value—0.73 MTCE per short ton of paper recovered—falls between the higher value for 2000 and the lower values for later years in the simulation period. We selected this value to approximate the short-term carbon sequestration benefits of source reduction and recycling because it balances the following: (1) relatively high carbon sequestration benefits will be achievable in the near term; (2) forest carbon sequestration benefits drop somewhat over time; and (3) more uncertainty is associated with the long-term carbon sequestration effects and market response (because model predictions far into the future are more uncertain than near-term predictions). In sum, we believe that the value for the year 2010 strikes the best balance in capturing the relatively higher short-term benefits of forest carbon sequestration and recognizing that these benefits decline over time.[25]

Using the forest carbon sequestration estimate for paper recovery, we developed estimates for forest carbon sequestration associated with source reduction of paper, as shown in Exhibit 3-9. We estimated source reduction values under two assumptions: that source reduction displaces only virgin inputs, and that it displaces the current mix of virgin and recycled inputs.[26] We estimated that forest carbon sequestration for source reduction, assuming displacement of virgin inputs, is the same as for paper recovery. Although this approach for estimating the effects of source reduction does not consider the loss rates associated with paper recovery, we believe it is a reasonable first approximation. To estimate the forest carbon sequestration for source reduction assuming displacement of the current mix of inputs, we used an additional factor, i.e., the percentage of virgin inputs in the current mix of inputs. For this calculation (column "d" in Exhibit 3-9), we account for the fact that displacement of recycled inputs does not have any impact on forest carbon sequestration.

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[25] The impact of increased paper recycling and source reduction on forest growing stock inventories (3 billion cubic feet in addition to the baseline scenario of 541 cubic feet in 2030, as shown in Exhibit 3-4) is only 0.5 percent. This amount is less than the likely statistical error in measuring the inventories. Although the estimated effect is a small proportion of the total inventory, the relationship between recycling and stocks is clear, and the magnitude of the effect is plausible and is significant on a per-ton basis.

[26] Source reduction may conceivably displace 100 percent virgin inputs if the quantity of paper recovered does not change with source reduction, and all recovered paper is used to make new paper. In that case, if the quantity of paper manufactured is reduced through source reduction, all of the reduction in inputs would come from virgin inputs. It is more likely, however, that source reduction reduces both virgin and recycled inputs.

Exhibit 3-8
Increased Forest Carbon Storage Per Ton of Paper Recovered

Cumulative Change Between the Baseline and High Paper Recovery Scenarios for:	2000	2010	2020	2030	2040
A. Forest Carbon Stocks* (million MTCE)	24.0	41.9	42.2	39.7	41.9
B. Wood-in-Use Stocks (million MTCE)	-7.0	-8.0	-4.0	-2.0	-2.0
C. Incremental Carbon Stored (million MTCE) [A+B]	17.0	33.9	38.2	37.7	39.9
D. Incremental Paper Recovery (million short tons)	19.7	46.2	81.4	81.4	81.4
E. Incremental Carbon Sequestration (MTCE/ton) [C/D]	0.9	0.7	0.5	0.5	0.5

*Includes trees and understory.

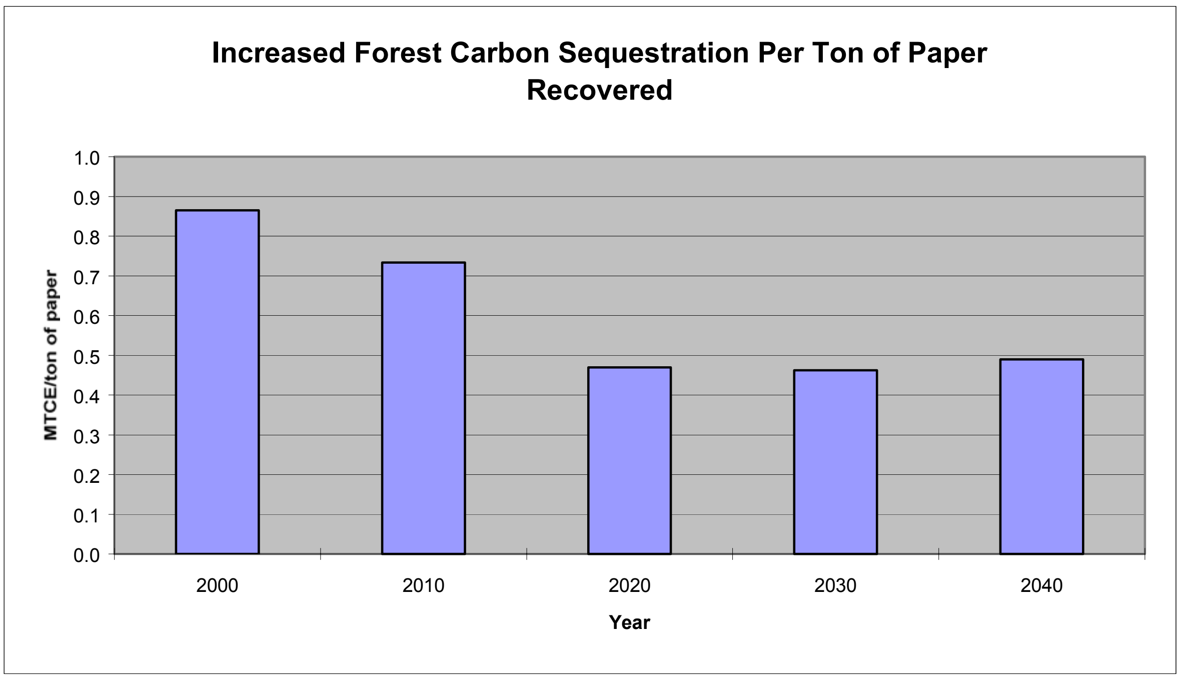

Exhibit 3-9
Forest Carbon Sequestration Per Ton of Paper Product Recycled or Source Reduced

(a) Material	(b) Recycling, Recovering 1 Incremental Ton of Paper (MTCE)	(c) Source Reduction, Assuming Displacement of 1 Ton of Paper Made from the Virgin Inputs (MTCE)	(d) Percent Virgin Inputs in the Current Mix of Inputs	(e) (e = b * d) Source Reduction, Assuming Displacement of One Ton of Paper Made From the Current Mix of Virgin and Recycled Inputs (MTCE)
Corrugated Cardboard	0.73	0.73	41%	-0.30
Magazines/ Third-class Mail	0.73	0.73	84%	-0.61
Newspaper	0.73	0.73	49%	-0.36
Office Paper	0.73	0.73	67%	-0.49
Phonebooks	0.73	0.73	89%	-0.66
Textbooks	0.73	0.73	87%	-0.64

Exhibit 3-10 displays the results of the analysis for dimensional lumber and medium-density fiberboard (the results are the same for both of these wood products). As shown in the top of the exhibit, the ratio of carbon stored per ton of reduced harvest is 0.99 MTCE/metric ton wood for 2010. Using the system efficiencies for wood products conversion rates and expressing emission factors in MTCE per short ton, the effects on the forest pool as of 2010 are the following:

- Recycling: 0.79 MTCE/ton
- Source reduction: 0.98 MTCE/ton

As noted earlier, recycling and source reduction would reduce the amount of carbon in the wood products pool; this effect is shown in the middle section of Exhibit 3-10. The bottom section shows the effect of summing the increase in forest carbon and the decrease in product pool carbon. Using 2010 as the most relevant period, the results are the following:

- Recycling: 0.69 MTCE/ton
- Source reduction: 0.50 MTCE/ton

Recycling has higher net carbon storage. Although it has a lower rate of forest carbon sequestration than source reduction, it also has a much smaller decrement in carbon storage in the product pool.

Exhibit 3-10
Increase in Forest Carbon per Unit Change in Harvest

Emission factor -- increase in forest carbon (trees + understory) per unit change in harvest Based on density and carbon content of softwoods in Southeast & South Central Region, Pine Forest Type					
	2000	**2010**	**2020**	**2030**	**2040**
Per ton reduced wood harvest (MT/MT)	0.96	0.99	0.99	0.99	0.97
Per ton reduced carbon harvest (MT/MT)	1.81	1.86	1.87	1.86	1.83
Per ton increased recycling (MT/short ton)	0.77	0.79	0.79	0.79	0.78
Per ton reduced prodn of solid wood product (source reduction) (MT/short ton)	0.96	0.98	0.99	0.98	0.97

Emission factor -- change in product pool carbon per unit change in recycling or source Based on carbon content of softwoods in Southeast & South Central Region, Pine Forest Type					
	2000	**2010**	**2020**	**2030**	**2040**
Per ton increased recycling (MT/short ton)	-0.10	-0.10	-0.10	-0.10	-0.10
Per ton reduced prodn of solid wood product (source reduction) (MT/short ton)	-0.48	-0.48	-0.48	-0.48	-0.48

Emission factor -- increase in forest + product pool carbon per unit change in recycling or Based on carbon content of softwoods in Southeast & South Central Region, Pine Forest Type					
	2000	**2010**	**2020**	**2030**	**2040**
Per ton increased recycling (MT/short ton)	0.67	0.69	0.70	0.69	0.68
Per ton reduced prodn of solid wood product (source reduction) (MT/short ton)	0.48	0.50	0.51	0.50	0.49

3.8 LIMITATIONS

Any analysis based on a complex system of models is subject to the limitations introduced by each model in the system. The limitations of each component model derive from (1) the assumptions made in developing the model; (2) the input equations used in the model; and (3) the potential impact of factors not included in the model. Because of these limitations, the actual behavior of markets for paper, wood, and other forest products (and the actual choices made by owners of private forestland) could differ from those predicted by the system of forest models. We believe that most of these limitations would tend to bias estimates under the baseline and high recycling scenarios in the same direction, so that the estimated *differences* between the two scenarios should be relatively accurate. Some limitations could result in unequal bias in the estimates, however, leading to biased estimates of the differences.

This section first discusses limitations associated with the geographic scope of the analysis. Secondly, we discuss limitations that could bias the estimates. Limitations that could bias both scenarios in the same direction are listed next. This section concludes with a brief discussion of the uncertainties introduced by the choice of a time period over which incremental forest carbon sequestration is estimated.

3.8.1 Limitations of Geographic Scope of Analysis and Results

Although the goal of this analysis is to estimate the impact of paper recycling and source reduction on GHG emissions in the *United States*, the actual effects would occur in Canada and other countries as well.

- The USDA-FS models treat forest product markets in the United States and Canada as a single integrated economic and biological system. But they do not treat Canadian forest inventories in the same way and degree of detail as U.S. forest inventories. The estimated impacts of increases in recycling and source reduction were treated as impacts on U.S. forests. Because much of the economically marginal paper production is from Canadian pulp sources, source reduction, in particular, would lower demand for Canadian timber. In any case, U.S. and Canadian forests actually would share the effects.
- More than 20 percent of the paper currently recovered in the two countries is exported. Some proportion of the increased amounts of recycled paper—probably more than 20 percent—would undoubtedly be exported. Current exports comprise 43 percent of the world trade in recovered paper. The major buyers of this paper are developing countries in Asia and Latin America, with Korea, Taiwan, and Mexico being major destinations. The alternative sources of fiber for the paper industry in these countries are pulp and fiber from non-forest sources (agricultural refuse, hemp, bamboo, and rubber and palm oil trees). Very little comes from forest harvests. Forests in these countries, however, are not necessarily managed on a sustainable basis. It is difficult to determine which of these effects would dominate—displacement of non-forest fiber (with no forest carbon impact) or displacement of unsustainably managed forest fiber (with a benefit larger than that in U.S. forests).[27]
- NAPAP does not account for any effects of lower pulpwood prices (due to higher paper recycling rates) on net exports of U.S. pulpwood to non-Canadian markets. Lower pulpwood prices would be expected to result in increased exports and possibly changes in foreign timber inventories. Though U.S. pulpwood exports are currently less than 1 percent of U.S. pulpwood production, some virgin pulp fiber is now being exported from southern and western ports in the form of pulp chips. The future potential for pulp chip exports is difficult to estimate.
- The competition to U.S. and Canadian exports of both recovered and newly manufactured paper is likely to come from two sources. First, all other developed countries are also likely to intensify recycling and source reduction programs, with additional recovery of paper fiber. Second, a major developing source of fiber for paper is the establishment of intensive forest plantations in tropical and southern hemisphere countries, particularly Australia, Brazil, Chile, Indonesia, New Zealand, and South Africa. The effect of additional world sources of paper fiber from developed countries on these forest plantation programs is difficult to estimate.

3.8.2 Limitations Expected to Bias the Results

Two limitations in the system of forest sector models could result in biased estimates of the incremental forest carbon sequestration from increased paper recycling. The limitations are as follows:

- The modeling system does not account for any conversion of U.S. forestland to farmland or rangeland that might occur in response to lower prices for pulpwood due to higher paper recycling rates. The NAPAP model does not account for potential changes in timber inventory in the near term due to lower harvests associated with higher paper recovery. Nor does it account for potential changes in forest acreage in the longer term if higher paper recovery depresses pulpwood prices enough to induce landowners to convert forested acreage

[27] A comprehensive description of the world paper industry, its fiber sources, and environmental concerns can be found in International Institute for Environment and Development (IIED), 1996, *Towards a Sustainable Paper Cycle,* IIED: London, 258 pp. This study, prepared for the World Business Council for Sustainable Development, treats many of the issues covered in this chapter, but on a global basis.

to other uses. The TAMM and ATLAS models likewise do not allow for long-term changes in forested acreage due to increased paper recovery. These effects, however, may be small. Converting forestland to agriculture or to industrial, commercial, or residential uses is far more likely to result from much higher land values for crops or development, if the land is suitable or in a favorable location.

- This analysis did not consider carbon storage in forest soils and forest floors, because of the high level of uncertainty in projecting changes in carbon storage. Nonetheless, projections of carbon storage in forest soils and floors under the baseline and high recycling scenarios, as generated by the FORCARB model, suggest that incremental carbon storage under the high recycling scenario could be slightly higher than shown here, if storage in soils and the forest floor were included.

3.8.3 Limitations Not Expected to Bias the Results

We expect that several limitations in the system of forest models would bias—to about the same extent—the estimates of forest carbon sequestration in the baseline and high recycling scenarios. The limitations thus would not result in significant bias in the estimate of the *difference* in forest carbon sequestration between the two scenarios. These limitations are as follows:

- The macroeconomic forecasts used in the models (e.g., for population growth and growth in per-capita gross domestic product) are simply forecasts, and may turn out to be inaccurate;
- The historical supply and demand functions used in the models may change in the future. For example, (1) demand for newspaper may drop sharply due to competition from electronic news media, or (2) improved technologies or tree diseases not anticipated in the models may significantly change the cost of producing forest products; and
- Future harvests from public forestland may be different from those projected.

3.8.4 The Use of a Point Estimate for Forest Carbon Sequestration

As shown in Exhibit 3-8, estimates of forest carbon sequestration due to increased paper recycling vary over time. As noted above, in choosing a single point estimate, we selected the time period that best balances the competing criteria of (1) capturing the long-term forest carbon sequestration effects, and (2) limiting the uncertainty inherent in projections made well into the future. The range of forest carbon sequestration estimates over time, and the limitations of the analysis discussed above, indicate that there is considerable uncertainty in the point estimate selected. In comparison to the estimates of other types of GHG emissions and sinks developed in other parts of this analysis, the magnitude of forest carbon sequestration is relatively high. Based on these forest carbon sequestration estimates, source reduction and recycling of paper are found to have substantial net GHG reductions. Because paper products comprise the largest share of municipal waste generation (and the largest volumes of waste managed through recycling, landfilling, and combustion), it is important to bear in mind the uncertainty in the forest carbon sequestration values when evaluating the results of this report.